



Biomass-to-electricity: Analysis and optimization of the complete pathway steam explosion – enzymatic hydrolysis – anaerobic digestion with ICE vs SOFC as biogas users

M. Santarelli ^{a,*}, S. Barra ^a, F. Sagnelli ^b, P. Zitella ^b

^a Dipartimento Energia, Politecnico di Torino, Corso Duca degli Abruzzi 24, 10129 Torino, Italy

^b BioEnergy Lab, Environment Park, Via Livorno 61, 10129 Torino, Italy

ARTICLE INFO

Article history:

Received 14 April 2012

Received in revised form 30 June 2012

Accepted 5 July 2012

Available online 20 July 2012

Keywords:

Biomass-to-electricity

Experimental analysis

Modeling

ICE

SOFC

ABSTRACT

The paper deals with the energy analysis and optimization of a complete biomass-to-electricity energy pathway, starting from raw biomass towards the production of renewable electricity.

The first step (biomass-to-biogas) is based on a real pilot plant located in Environment Park S.p.A. (Torino, Italy) with three main steps ((1) impregnation; (2) steam explosion; (3) enzymatic hydrolysis), completed by a two-step anaerobic fermentation.

In the second step (biogas-to-electricity), the paper considers two technologies: internal combustion engines and a stack of solid oxide fuel cells.

First, the complete pathway has been modeled and validated through experimental data. After, the model has been used for an analysis and optimization of the complete thermo-chemical and biological process, with the objective function of maximization of the energy balance at minimum consumption.

The comparison between ICE and SOFC shows the better performance of the integrated plants based on SOFC.

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1. Introduction

Bio-hydrogen and biogas production via dark anaerobic fermentation has shown in recent years to be worth of interest due to environmental, economic and energetic advantages deriving from the possibility of processing residues as renewable sources of energy. In particular, experimental tests have shown that double stage mesophilic systems for the co-production of bio-hydrogen and biogas leads to an increase of both the overall yield and the methane percentage in the biogas stream if compared with the traditional one-stage process for biogas production, as outlined by Parawira et al. (2004) and Zhu et al. (2007).

Among the different typology of available substrates (wastewater effluents, residual crops, organic wastes, agro-industrial residues), lignocellulosic biomass is particularly suitable for energy applications because of its wide availability, low cost and near-zero green-house gas emissions. Lignocellulosic biomass (i.e., straw, grass, wood residues, etc.) consists of lignin, cellulose and hemicellulose of which lignin is the most resistant to the anaerobic degradation performed by fermentative bacteria. The hydrolytic phase of fermentation is delayed or even inhibited when cellulose is encrusted in lignin (as described by Gallert and Winter (2005) and

Fernandes et al. (2009)) preventing the accessibility of cellulose to cellulolytic enzymes. The goal of the application of chemical, physical and/or enzymatic fractionation is to remove/separate lignin, reduce the degree of cellulose crystallinity, and increase the surface area of biomass, resulting in an enhancement of mobilization of sugars from lignocellulosic substrate (Bauer et al., 2009).

Steam explosion and enzymatic pre-treatments have been applied on different typologies of lignocellulosic biomass by identifying the optimal conditions for the release of glucose and xylose, as described by Cao et al. (2012) and Horn et al. (2011).

Some scientific studies have shown the successful combination of steam explosion pre-treatment with enzymatic hydrolysis for enhancing biogas production in fermentative processes (Petersson et al., 2007).

Since the pre-treatment process may present not negligible energy consumptions, a detailed energy analysis is mandatory. The more complex the transformation process is, the more important is a detailed energy analysis of every step of the entire process and of the global energy pathway biomass-to-electricity, in order to avoid huge investments in processes with a very poor energy efficiency. Moreover, it is important to select the most sensitive parameters of the process, in order to derive an optimization strategy for the design and operation of the complete plant.

The analysis could not be considered complete if it does not integrate the choice of the final technology of biogas transformation to

* Corresponding author. Tel.: +39 011 090 4487; fax: +39 011 090 4499.

E-mail address: massimo.santarelli@polito.it (M. Santarelli).

Nomenclature

| | | | |
|-----------|--|-----------------------|--|
| A_i | heat transfer surface for the i th component [m^2] | PHS | amount of pre-hydrolyzed sugar recovered after the steam explosion [kg] |
| AI | acetic acid impregnation | Pot _{biogas} | chemical power (lower heating value) of the anaerobic fermentation outlet stream [kJ/kg] |
| Air | amount of compressed air consumed [m^3/h] | p_{xy} | surface fitting coefficient |
| C | coefficient of the enzymatic hydrolysis model (function of the steam explosion temperature and duration) | R_{mH} | maximum bio-hydrogen production rate in the two stages anaerobic fermentation [mL/h] |
| C% | percentage of cellulose present in the dry wheat straw [%] | S_0 | substrate concentration [g/L] |
| CHP | combined heat and power plants | SE | steam explosion |
| cp_j | specific heat at constant pressure for the j th component [$\text{kJ h}/\text{kg K}$] | SOFC | solid oxide fuel cells |
| DS | amount of dry wheat straw [kg] | T | process temperature [$^{\circ}\text{C}$] |
| E% | percentage of hemicellulose present in the dry wheat straw [%] | T^* | process temperature normalized |
| E_0 | enzyme concentration [g/L] | T_{SE} | steam explosion temperature [$^{\circ}\text{C}$] |
| EH | enzymatic hydrolysis | TDM | total dry matter present after the steam explosion [%] |
| EI | ethanol impregnation | T | duration of the process [h] |
| G | grinding system | t^* | duration process normalized |
| G_0 | initial glucose concentration | t_{SE} | steam explosion retention time [min] |
| H | cumulative bio-hydrogen production in the two stages anaerobic fermentation [mL] | U_i | thermal transmittance equivalent for the i th component [$\text{kW}/\text{m}^2 \text{K}$] |
| HP | high pressure steam generator | $U_{f,i}$ | utilization factor for the i th component |
| HS | amount of hydrolyzed sugar recovered after the enzymatic hydrolysis [kg] | V_1 | volume of reactor used for the production of bio-hydrogen [m^3] |
| H_i | lower heating value [kJ/kg] | V_2 | volume of reactor used for the production of bio-methane [m^3] |
| ICE | internal combustion engines | W | electric power [kW] |
| K_1 | specific electric consumption of air compressor [$\text{kW h}/\text{m}^3$] | WI | water impregnation |
| K_2 | specific electric consumption of boiler [$\text{kW h}/\text{kW h}_{TH}$] | X | steam title present inside the reactor before the explosion |
| K_3 | specific electric consumption of high-pressure steam generator [$\text{kW h}/\text{kW h}_{TH}$] | Greek | |
| K_4 | specific electric consumption of low-pressure steam generator [$\text{kW h}/\text{kW h}_{TH}$] | Φ_1 | heat dissipation from pipe/pipes [kW] |
| K_e | constant rate of the enzymatic hydrolysis [g/L] | Φ_2 | heat dissipation from reactor/reactors [kW] |
| k_2 | rate of product formation in the enzymatic hydrolysis [1/h] | Φ_3 | heating of metal parts [kW] |
| k_{de2} | rate of deactivation of the enzyme [1/h] | Φ_4 | heating of process liquid [kW] |
| L% | percentage of lignin present in the dry wheat straw [%] | Φ_5 | heat for the air evacuation [kW] |
| LP | low pressure steam generator | Φ_6 | heat for the charge of SE reactor [kW] |
| M_j | mass for the j th component [kg] | Φ_7 | heat recovered by vapor [kW] |
| P | maximum cumulative bio-hydrogen production in the two stages anaerobic fermentation [mL] | Φ_8 | heating of water–glycol mixture [kW] |
| P_i | electrical power for the i th component [kW] | Φ_{TOT} | amount of heat consumed [kW_{TH}] |
| | | η_S | efficiency of the heat exchanger |
| | | Δ | lag phase in the two stages anaerobic fermentation [h] |
| | | P | steam density present inside the reactor before the explosion [kg/m^3] |

energy services (usually electricity and heat): in fact, this last technological choice could have a significant impact on the previous pre-treatment process (its structure and optimization) and in the complete energy balance (as the final technology is usually integrated with the previous process).

In this paper, the detailed energy analysis of a real complete plant biomass-to-electricity is described. It is a prototype plant located in Environment Park S.p.A. (Torino, Italy) used for the production of bio-hydrogen and biogas starting from biomass. The complete process is composed of a section of pre-treatment of the feedstock with three main steps ((1) impregnation; (2) steam explosion; (3) enzymatic hydrolysis), completed by a two-stage anaerobic fermentation process. The plant is completely instrumented, so the high number of feed points allows a deep analysis of its operation and of its energy balance.

Concerning the technologies considered for the final transformation of the biogas in energy (mainly electricity) services, two technologies emblematic in their diversity have been considered:

(1) internal combustion engines (ICE), a mature and widespread distributed option; (b) a stack of solid oxide fuel cells (SOFC), a future technology with very high conversion efficiencies (in particular electric). These choices will allow an analysis linked both to the state-of-the-art option (ICE) and to a near-to-medium future option (SOFC).

The performer analysis has outlined the following points:

- the criticalities of the process of transformation of wood to electricity, and the consequent ways to optimize it;
- the criticalities of the integration of the process with the final technology of biogas utilization, and the consequent ways to optimize it;
- the complete energy balance, and its critical points.

Therefore, the energy analysis outlines the conditions in which this biomass-to-electricity pathway could be considered of interest, and why at present it has not still reached a complete maturity.

2. Methods

2.1. Energy analysis of a biomass-to-biogas prototype: general description

The biogas production plant was designed as a prototype in view of an industrial scale-up and can rely on automatic controls and alarms, which guarantee a flexible management.

The pre-treatment plants are three (impregnation, steam explosion and enzymatic hydrolysis) and are designed to work in series or in parallel. These systems allow the treatment and the valorization of various types of biomass that are not directly fermentable.

The anaerobic fermentation plant is formed by two reactors in series that allow the simultaneous production of hydrogen and biogas (the process is more efficient than a single-stage system).

The auxiliary systems are: a system of grinding (G) (whit specific consumption equal to 0.03 kW h/kg), which reduces the biomass to the desired size; a low pressure steam generator (LP); a high pressure steam generator (HP); a boiler; an electric air compressor.

2.2. Main assumptions

Due to the heterogeneity of biomass, it was decided to concentrate the analysis by studying the effects of pre-treatment only on wheat straw, as it represents the main agricultural waste in northern Italy and central Europe.

The different chains of pre-treatment analyzed in this study are:

1. the enzymatic hydrolysis (EH);
2. the enzymatic hydrolysis (EH) preceded by steam explosion (SE) of impregnated straw with water (WI);
3. the enzymatic hydrolysis (EH) preceded by steam explosion (SE) of impregnated straw with acetic acid (AI);
4. the enzymatic hydrolysis (EH) preceded by steam explosion (SE) of impregnated straw with ethanol (EI).

A preliminary analysis of the results (Table 1) showed which of these chains was the most interesting pathway. To compare the results, the values were calculated referred to 1 kg of wheat straw processed.

All the pre-treatment processes analyzed are in batch, while the two-stage anaerobic fermentation has been considered as semi-continuous.

Therefore, this paper concentrates the analysis on the wheat straw impregnated in ethanol, pre-treated through steam explosion (SE) followed by enzymatic hydrolysis (EH), as it is the best combination in terms of energy balances.

2.3. Impregnation

2.3.1. Description

The impregnation is used to catalyze the subsequent steam explosion. With impregnation, the cellulose and hemicellulose present in the wheat straw become more pre-hydrolysable, and consequently the recovery of sugars can be increased.

This process is done in a tank (150 L), insulated and equipped with a heating jacket. Heating is provided by a boiler because the temperatures required for the process are less than 100 °C. The system is also equipped with valves and pumps for dosing of chemicals.

2.3.2. Modeling

The heat required for the process is given by the following equation:

Table 1

Comparison between the total consumption of processes, in terms of primary energy, and the biogas yield for the different pre-treatment chains, calculated for each kilogram of wheat straw treated. The table also shows the specific consumption. The total consume include the grinding consumption and the anaerobic fermentation consumption.

| Chain of pre-treatment | Total consume (primary energy) [kW h] | Yield of equivalent biogas [kW h] | Specific consumption [kW h/kW h] |
|------------------------|---------------------------------------|-----------------------------------|----------------------------------|
| 1 EH | 4.504 | 0.330 | 13.648 |
| 2 EH + SE + WI | 6.941 | 1.753 | 3.959 |
| 3 EH + SE + AI | 9.007 | 2.024 | 4.450 |
| 4 EH + SE + EI | 8.633 | 2.200 | 3.924 |

$$\Phi_{TOT} = \Phi_1 + \Phi_2 + \Phi_3 + \Phi_4 \quad (1)$$

$$\Phi_{TOT} = \sum_{i=1}^2 U_i A_i (T_i - T_0) + \sum_{j=3}^4 M_j c_{p_j} (T - T_0) / t \quad (2)$$

where the first summation calculates the heat lost from the pipes ($i = 1, \Phi_1$) and the reactor ($i = 2, \Phi_2$), and the third term calculates the heat needed for heating, in time t , the metal masses of the reactor ($i = 3, \Phi_3$) (during the necessary start up) and the last term the heat needed for heating, in time t , the process liquid + biomass ($i = 4, \Phi_4$).

The electricity required in the process is given by the following equation:

$$W_{TOT} = \sum_{i=1}^n P_i \cdot u_{f,i} + Air \cdot K_1 + \Phi_{TOT} \cdot K_2 \quad (3)$$

where the first summation calculates the electricity consumed by the i th not negligible components (u_f is the utilization factor), the second term the electricity consumed by the compressor for the pneumatic valves (where Air is the volumetric flow rate of the compressed air consumed) and the third term the electricity consumed by the boiler (where Φ_{TOT} is the heat consumed). K_1 and K_2 are constant that define, respectively, the electric specific consumption of compressor and boiler.

For the impregnation the only component considered is the regulation valve that serves the heating circuit.

The optimal condition of impregnation of the wheat straw with ethanol, corresponds to an impregnation of 18 h at 40 °C, with a concentration of 75% of ethanol, as reported by Zabihi et al. (2010).

2.4. Steam explosion

2.4.1. Description

The steam explosion is used to treat lignocellulosic biomass, because it destroys the structure of lignin and makes accessible the organic matter to the attack of enzymes and bacteria. The process is at the same time thermo-chemical and physical.

The steam explosion is made in a reactor (about 30 L) that cannot treat more than 2 kg of biomass reduced to chips of around 2 cm, insulated and equipped with a heating jacket. Heating is provided by a high-pressure steam generator because the temperatures required for the process are about 200 °C. The pseudo isenthalpic expansion is done in 0.2 s, towards a downstream cylinder with a volume of 550 L. The system is also equipped with valves for regulating the process.

2.4.2. Modeling

Fig. 1 shows the model considered for input and output of material and heat in the steam explosion system. The heat required for the process is given by the following equation:

$$\Phi_{TOT} = \Phi_1 + \Phi_2 + \Phi_3 + \Phi_5 + \Phi_6 - \Phi_7 \quad (4)$$

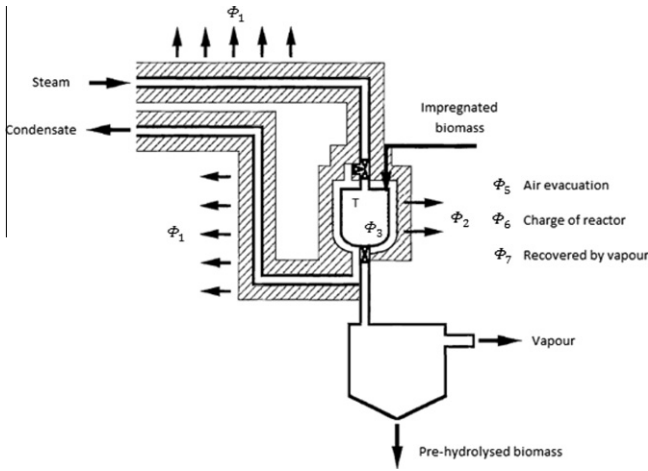


Fig. 1. Input and output of material and heat in the steam explosion system.

$$\Phi_{TOT} = \sum_{i=1}^2 U_i A_i (T_i - T_0) + M_3 c p_3 (T - T_0) / t + \Phi_5 + \Phi_6(T, \rho) - \Phi_7(x, \Phi_6) \quad (5)$$

where the sum calculates the heat lost from the pipes (Φ_1) and the reactor (Φ_2); the third term (Φ_3) calculates the heat needed for heating, in the time t , the metal masses of the reactor (during the start-up); the fourth term (Φ_5) indicate the heat consumed for the air evacuation; the fifth term (Φ_6) calculate the heat consumed for charging the reactor with high-pressure steam; the last term (Φ_7) calculates the heat recovered by the final condensation of the vapor generated after the explosion. Φ_5 is assumed constant and equal to the heat necessary to produce 0.1 kg of high pressure steam (used to evacuate the air inside the reactor). Φ_6 is function of temperature (process temperature T) and the density of the steam present inside the reactor. Φ_7 is function of steam title (x) present inside the reactor before the explosion, and the heat of condensation (equal to Φ_6).

The electricity required in the process is given by the following equation:

$$W_{TOT} = Air \cdot K_1 + \Phi_{TOT} \cdot K_3 \quad (6)$$

where the first term is the electricity consumed by the compressor for the pneumatic valves (where Air is the volumetric flow rate of the compressed air consumed) and the second term the electricity consumed by the high-pressure steam generator (where Φ_{TOT} is the heat consumed). K_1 and K_3 are constant that define, respectively, the electric specific consumption of compressor and of the high-pressure steam generator.

For the steam explosion all the electric components are considered negligible, due to the brevity of the process (order of minutes).

The yield from steam explosion is the quantity of sugar pre-hydrolyzed: it depends on the impregnation type and severity of the process (temperature T_{SE} and retention time t_{SE}). The formula that calculates the solid material (following the SE) percentage of initial solid material was obtained by a surface fitting of experimental data as reported by Zabihi et al. (2010):

$$TDM(t_{SE}, T_{SE}) = p_{00} + p_{10} \cdot t^* + p_{01} \cdot T^* + p_{20} \cdot t^{*2} + p_{11} \cdot t^* \cdot T^* + p_{02} \cdot T^{*2} + p_{21} \cdot t^{*2} \cdot T^* + p_{12} \cdot t^* \cdot T^{*2} + p_{03} \cdot T^{*3} \quad (7)$$

where $t^* = \frac{t-12.5}{5.71}$, $T^* = \frac{T-204.2}{16.26}$ $p_{00} = 59.27$, $p_{10} = -1.136$, $p_{01} = -7.182$, $p_{20} = 1.087$, $p_{11} = 0.9884$, $p_{02} = 0.2917$, $p_{21} = -0.7439$, $p_{12} = 0.1133$, $p_{03} = 1.151$.

Assuming that the loss is caused entirely by the hydrolysis of cellulose and hemicellulose, and knowing the initial composition of the treated wheat straw, the yield as a function of temperature and retention time can be derived.

$$PHS = DS \cdot [E\% + C\% + L\% - TDM(T_{SE}, t_{SE})] \quad (8)$$

2.5. Enzymatic hydrolysis

2.5.1. Description

The enzymatic hydrolysis is used to process wheat straw (pre-treated or not) in order to obtain simple sugars. In fact, the lignocellulosic polysaccharides, in contact with water and enzymes, are reduced, after a certain time, into monosaccharide such as glucose and xylose.

The enzymatic hydrolysis is made in a 120 L reactor and the biomass quantity treated may change as a function of the concentration. The reactor is insulated and equipped with a heating jacket. Heating is provided by a low-pressure steam generator. The steam does not heat the reactor directly but through a temperature control circuit (water and glycol in equal parts). This is made to precisely regulate the reactor temperature to avoid the death of enzymes, which are very sensitive to rapid temperature changes.

2.5.2. Modeling

Fig. 2 shows the model considered for input and output of material and heat in the enzymatic hydrolysis system. The heat required for the process is given by the following equation:

$$\Phi = \Phi_1 + \frac{\Phi_2 + \Phi_3 + \Phi_4 + \Phi_5}{\eta_s} \quad (9)$$

$$\Phi_{TOT} = U_1 A_1 (T_1 - T_0) + \frac{U_2 A_2 (T_2 - T_0)}{\eta_s} + \sum_{j=3}^{3.4.8} \frac{M_j c p_j (T - T_0)}{\eta_s \cdot t} \quad (10)$$

where the first and the second term are respectively the heat lost from the pipes and from the reactor; the sum calculates the heat needed (during the start-up phase) for heating, the metal masses of the reactor ($j = 3, \Phi_3$), for the heating of the liquid used in the process ($j = 4, \Phi_4$) and for the heating of water-glycol mixture ($j = 8, \Phi_8$), in the time t . The efficiency of the heat exchanger is considered equal to 0.9.

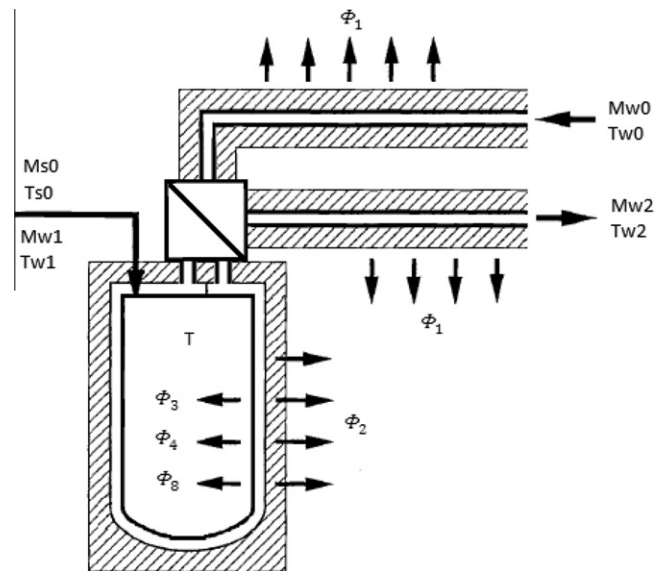


Fig. 2. Input and output of material and heat in the enzymatic hydrolysis system.

The electricity required in the process is given by the following equation:

$$W_{TOT} = \sum_{i=1}^3 P_i \cdot u_{f,i} + Air \cdot K_1 + \Phi_{TOT} \cdot K_4 \quad (11)$$

where the first summation calculates the electricity consumed by the i th not negligible component, the second term the electricity consumed by the compressor (where Air is the volumetric flow rate of compressed air consumed) and the third term the electricity consumed by the boiler (where Φ_{TOT} is the heat consumed). K_1 and K_4 are constant that define, respectively, the electric specific consumption of compressor and of the low-pressure steam generator. For the enzymatic hydrolysis the component considered are the agitator ($i = 1$), the pump for the recirculation of thermostat liquid ($i = 2$) and the regulation valve that serves the heating circuit (steam side) ($i = 3$).

The enzymatic hydrolysis yield is the quantity of hydrolyzed sugar: it depends on the impregnation type, on the severity of the steam explosion, on the enzyme concentration and the retention time of the process.

The equation is based on a kinetic model of Zhang et al. (2010):

$$HS = S_0 \cdot \left\{ 1 - \left[1 + \frac{K_e \cdot E_0}{K_e + E_0} \cdot k_{de2} \cdot t \right]^{-\frac{k_2}{K_e \cdot k_{de2}}} \right\} \quad (12)$$

where HS is the glucose concentration [g/L], S_0 is the substrate concentration [g/L], E_0 is the enzyme concentration [g/L], K_e is the constant rate [g/L], k_{de2} is the rate of deactivation of the enzyme [1/h], k_2 is the rate of product formation [1/h].

For the insoluble fibers of wheat straw, after a steam explosion for 5 min at 200 °C, the parameters of the above equation are: K_e [g/L] = 16.8597, k_{de2} [1/h] = 0.4011, k_2 [1/h] = 0.4732.

The equation is valid for times ranging from 0 to 100 h and enzyme concentration ranging from 1.33 to 25.33 g/L (99 FPU/L to 1876 FPU/L).

As mentioned above, the impregnation and the subsequent steam explosion affect the enzymatic hydrolysis's yield. It was decided to add a correction factor C to the model described above, for making the new formulation also depending on the type of impregnation and the severity of steam explosion (temperature and duration).

$$HS = C(T_{SE}, t_{SE}) \cdot S_0 \cdot \left\{ 1 - \left[1 + \frac{K_e \cdot E_0}{K_e + E_0} \cdot k_{de2} \cdot t \right]^{-\frac{k_2}{K_e \cdot k_{de2}}} \right\} \quad (13)$$

The coefficient C (function of the steam explosion temperature and duration) was obtained by a surface fitting of experimental data from Zabihi et al. (2010):

$$C(t_{SE}, T_{SE}) = p_{00} + p_{10} \cdot t^* + p_{01} \cdot T^* + p_{20} \cdot t^{*2} + p_{11} \cdot t^* \cdot T^* + p_{02} \cdot T^{*2} + p_{21} \cdot t^{*2} \cdot T + p_{12} \cdot t^* \cdot T^{*2} + p_{03} \cdot T^{*3} + p_{22} \cdot t^{*2} \cdot T^2 + p_{13} \cdot t^* \cdot T^{*3} + p_{04} \cdot T^{*4} + p_{23} \cdot t^{*2} \cdot T^{*3} + p_{14} \cdot t^* \cdot T^{*4} + p_{05} \cdot T^{*5} \quad (14)$$

where $t^* = \frac{t_{SE}-12}{5.548}$, $T^* = \frac{T_{SE}-204}{16.01}$, $p_{00} = 138.900$, $p_{10} = 9.197$, $p_{01} = 22.510$, $p_{20} = -3.255$, $p_{11} = -7.698$, $p_{02} = 7.650$, $p_{21} = 5.870$, $p_{12} = -11.100$, $p_{03} = -6.873$, $p_{22} = -0.542$, $p_{13} = -1.511$, $p_{04} = 9.158$, $p_{23} = -1.790$, $p_{14} = 2.409$, $p_{05} = -0.142$.

2.6. Two stage anaerobic fermentation (AF)

2.6.1. Description

The plant in Environment Park is composed of a two-step fermentation: a reactor used for the production of bio-hydrogen, completed by a reactor for the production of biogas (CH_4/CO_2 60/40), which could operate both in batch or in continuous.

In the bio-reactor for the production of bio-hydrogen is present a recirculation system through a peristaltic pump and two 3-way valves. The final digester for the production of biogas (which optimize the complete recovery of chemical energy from the biomass into biogas) has a recirculation system too, through a peristaltic pump and a 3-way valve. Both the reactor is made in AISI316, and has a heating jacket and a thermal insulator to optimize the thermal regulation of the process. For both the reactor, heating is provided by a boiler.

2.6.2. Modeling

Fig. 3 shows the model considered for input and output of material and heat in the anaerobic fermentation system. To maintain the operation conditions of the reactor, thermal energy is supplied, to fix the process temperature at 35 °C. The inlet biomass is already in temperature (coming from the previous processes), while the outlet streams are in equilibrium with the process temperature:

$$T_{w0} = T_{w1} = T \quad (15)$$

The energy balance is:

$$\Phi_{TOT} = \Phi_1 + \Phi_2 \quad (16)$$

$$\Phi_{TOT} = U_1 A_1 (T_1 - T_0) + U_2 \cdot A_2 \cdot (T - T_0) \quad (17)$$

where the first and the second term are respectively the heat lost from the pipes and from the bio-hydrogen and biogas reactors.

The electricity required in the process is given by the following equation:

$$W_{TOT} = \sum_i P_i \cdot u_{f,i} + \Phi_{TOT} \cdot K_2 \quad (18)$$

where the first summation calculates the electricity consumed by the i th not negligible component (essentially, the two peristaltic pump) and the second term the electricity consumed by the boiler (where Φ_{TOT} is the heat consumed). K_2 is a constant that define the electric specific consumption of the boiler.

The anaerobic fermentation yield, in case of a two-steps process (bio-hydrogen + biogas) is linked to the bio-hydrogen + biogas yield. The modeling of this yield has been described by a modified Gompertz equation (from Datar et al. (2007)) in case of a continuous process:

$$H = P \cdot \exp \left\{ -\exp \left[\frac{R_{mH} \cdot e}{p} (\lambda - t) + 1 \right] \right\} \quad (19)$$

where H is the cumulative bio-hydrogen production [mL], P is the maximum cumulative bio-hydrogen production [mL], R_{mH} is the

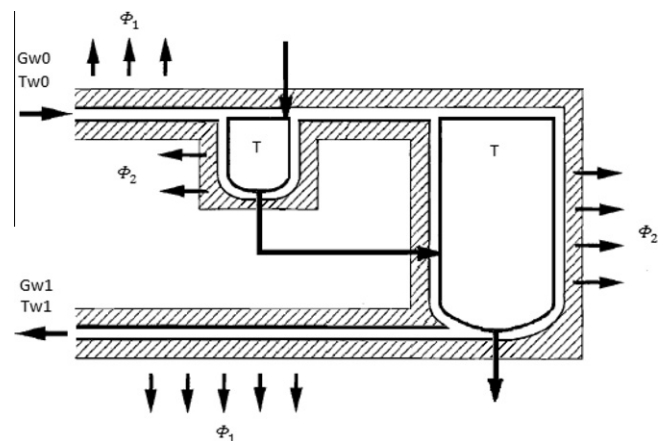


Fig. 3. Input and output of material and heat in the anaerobic fermentation system.

Table 2

Compositions (indicative) of bio-hydrogen and biogas streams.

| | H ₂ (%) | CH ₄ (%) | CO ₂ (%) |
|--------------|--------------------|---------------------|---------------------|
| Bio-hydrogen | 30–45 | 0 | 55–70 |
| Biogas | 0 | 70–85 | 15–30 |

maximum bio-hydrogen production rate [mL/h], λ is the lag phase [h].

The studies described in the paper of [Datara et al. \(2007\)](#), outline how the sugars with highest concentration in the biomass (glucose and xylose) have similar yields in terms of bio-hydrogen production. Therefore, is possible to analyse the bio-hydrogen production from known processes of glucose fermentation. The same paper shows significant values of λ , and describes how to obtain, from a fitting of experimental data, the equations of the parameters P and R_{mH} as a function of the initial glucose concentration G_0 :

$$\lambda[h] = 15$$

$$P[\text{mL/L}] = -5.0754 \cdot G_0^2 + 293.21 \cdot G_0 + 89.958 \quad R^2 = 0.9851 \quad (20)$$

$$R_{mH}[\text{mL/Lh}] = -0.6104 \cdot G_0^2 + 36.534 \cdot G_0 + 50.515 \quad R^2 = 0.9746$$

Finally, concerning the biogas reactor, the maximum rate of methane production can be obtained from the experimental data described in the paper of [Zhu et al. \(2007\)](#). In particular, there is a relationship between the maximum rate of production of methane and bio-hydrogen in a two-step digestion of the same biomass; this relationship can be then used to express the maximum methane production rate as a function of the initial glucose concentration.

$$\frac{R_{mH_2}(G_0)}{R_{mCH_4}(G_0)} = \frac{597.2}{27.7} \left[\frac{\text{mL/Lh}}{\text{mL/Lh}} \right] \quad R_{mCH_4} = \frac{R_{mH_2}(G_0)}{17.91} \quad (21)$$

From the expressions of the maximum production rates of bio-hydrogen and methane, it is obtained the chemical power (lower heating value) of the anaerobic fermentation outlet stream as a function of the initial glucose concentration:

$$\text{Pot}_{\text{biogas}}(G_0) = R_{mH_2}(G_0) \cdot V_1 \cdot Hi_{H_2} + R_{mCH_4}(G_0) \cdot V_2 \cdot Hi_{CH_4} \quad (22)$$

where V_1 and V_2 are respectively the volume of reactor used for the production of bio-hydrogen and the volume of reactor used for the production of bio-methane.

3. Results

3.1. Energy pathway optimization: ICE or SOFC

The biogas, produced with the discussed process, could be considered as an interesting renewable fuel for energy production on a local scale. In this sense, two very different energy technologies have been analyzed: (1) internal combustion engines (ICE), a mature and widespread distributed option; (b) a stack of solid oxide fuel cells (SOFC), a future technology with very high conversion efficiencies (in particular electric).

In particular, the analysis is interesting especially considering the system integration of the biogas production and utilization plants: part of the produced electric power and of the recovered thermal power can be used to sustain the biogas production pro-

Table 4

Electric and global efficiency of a SOFC stack as a function of the composition of the anode biogas fuel.

| CH ₄ [%] | H ₂ [%] | CO ₂ [%] | Electric efficiency [%] | Global efficiency [%] |
|---------------------|--------------------|---------------------|-------------------------|-----------------------|
| 60 | 10 | 30 | 49.4 | 74.8 |
| 70 | 0 | 30 | 49.9 | 74.6 |
| 60 | 0 | 40 | 49.7 | 75.1 |
| 70 | 10 | 20 | 49.8 | 74.5 |
| 50 | 10 | 40 | 49.0 | 75.4 |
| 100 | 0 | 0 | 50.8 | 74.0 |
| 50 | 50 | 0 | 48.8 | 74.8 |
| 0 | 100 | 0 | 45.5 | 78.9 |
| 0 | 50 | 50 | 38.1 | 84.1 |

cesses (pre-treatment, fermentation) to reach a self-sustainability of the energy chain.

As discussed, the two step fermentation produces two gas streams, a stream of bio-hydrogen and a stream of classic biogas, with the following indicative compositions ([Table 2](#)).

In particular, the methane fraction in the biogas is higher than the standard one because the double fermentation step allows a better use of the substrate.

From the previous paragraph, it results 5.6 S m³ of biogas for every S m³ of bio-hydrogen. Therefore, a mixing of the two streams is considered, with a composition (for the following analysis) of 9.8% of H₂ and 54.8% of CH₄, with LHV of 5.12 kW h/m³.

3.2. Internal combustion engines (ICE)

The considered ICE is produced by Jenbacher (http://www.ge-energy.com/prod_serv/products/recip_engines/en/index.htm), which has modules operating with such kind of biogas. The two extreme size of the engines at catalogue have been considered: Type 208 and Type 620.

The biogas has a significant hydrogen fraction: in literature, several studies are available which demonstrate an improvement of the electric efficiency in ICE fed with hydrogen-rich biogas streams; in particular ([Jeong et al., 2009](#)) supply experimental data concerning the improvements: 5% H₂ yields + 3.34% efficiency, 10% H₂ yields + 4.58% efficiency, 15% H₂ yields + 5.26% efficiency.

In the case of 10% H₂, the electric efficiencies and thus the power of the Jenbacher ICE become as in [Table 3](#):

3.3. Solid oxide fuel cells (SOFC)

For the analysis, a model developed at Politecnico di Torino ([Lanzini and Leone, 2010](#)) has been considered, expressing the electric and global efficiency of a SOFC stack as a function of the composition of the anode biogas fuel, shown in [Table 4](#):

The considered biogas stream has roughly 55% CH₄, 10% H₂ and 35% CO₂, thus with efficiency values of $\eta_{EL} = 49.2\%$, $\eta_{TOT} = 75.1\%$.

3.4. Plant optimization 1

The first procedure of plant optimization is centered on the biogas production step: the aim is the maximum biogas production at the lowest energy consumption (both electric and thermal). After the optimum point has been selected, the analysis has been made

Table 3Jenbacher ICE characteristics in case of 10% H₂-rich biogas streams.

| | Electric power [kW] | Electric efficiency [%] | Thermal power [kW] | Thermal efficiency [%] | Global efficiency [%] |
|----------|---------------------|-------------------------|--------------------|------------------------|-----------------------|
| Type 208 | 278 | 43.7 | 276 | 41.4 | 85.1 |
| Type 620 | 2706 | 44.3 | 2468 | 40.4 | 84.7 |

Table 5

Plant optimization 1 and 2 (values in kWh).

| Technology | Biogas energy | Produced electric energy | Consumed electric energy | Electrical surplus | Produced thermal energy | Consumed thermal energy | Thermal deficit |
|-----------------------------|---------------|--------------------------|--------------------------|--------------------|-------------------------|-------------------------|-----------------|
| <i>Plant optimization 1</i> | | | | | | | |
| ICE Type 208 | 2.299 | 1.005 | 0.880 | 0.124 | 0.952 | 5.947 | 4.995 |
| ICE Type 620 | 2.299 | 1.019 | 0.880 | 0.138 | 0.929 | 5.947 | 5.018 |
| SOFC | 2.299 | 1.131 | 0.880 | 0.251 | 0.596 | 5.947 | 5.352 |
| <i>Plant optimization 2</i> | | | | | | | |
| ICE Type 208 | 1.894 | 0.828 | 0.628 | 0.200 | 0.784 | 5.385 | 4.601 |
| ICE Type 620 | 1.899 | 0.841 | 0.630 | 0.212 | 0.767 | 5.390 | 4.623 |
| SOFC | 1.936 | 0.952 | 0.646 | 0.307 | 0.501 | 5.424 | 4.923 |

in the case of the integrated biogas production + utilization system: at the given value of biogas input, the net energy produced is analyzed. The results are presented as normalized values referred to the unit of starting biomass (the primary fuel), that is 1 kg of wheat straw. Therefore, in the case of wheat straw pre-impregnated with ethanol, steam explosion and enzymatic hydrolysis, the results are reported in Table 5. The electric energy surplus is assured, while the recovered thermal energy is never sufficient to sustain the biogas production process. Also, the higher SOFC electric efficiency allows quite a duplication of the net electric energy: therefore, it is shown that the electric balance of the

integrated system has a high sensitivity to the electric efficiency of the energy production technology.

3.5. Plant optimization 2

The second procedure of plant optimization is centered on the overall energy balance: the aim is the maximization of the net electric energy at the lowest thermal energy deficit. Even in this case, the results are presented as normalized values referred to the unit of starting biomass (the primary fuel), that is 1 kg of wheat straw. Therefore, in the case of wheat straw pre-impregnated with

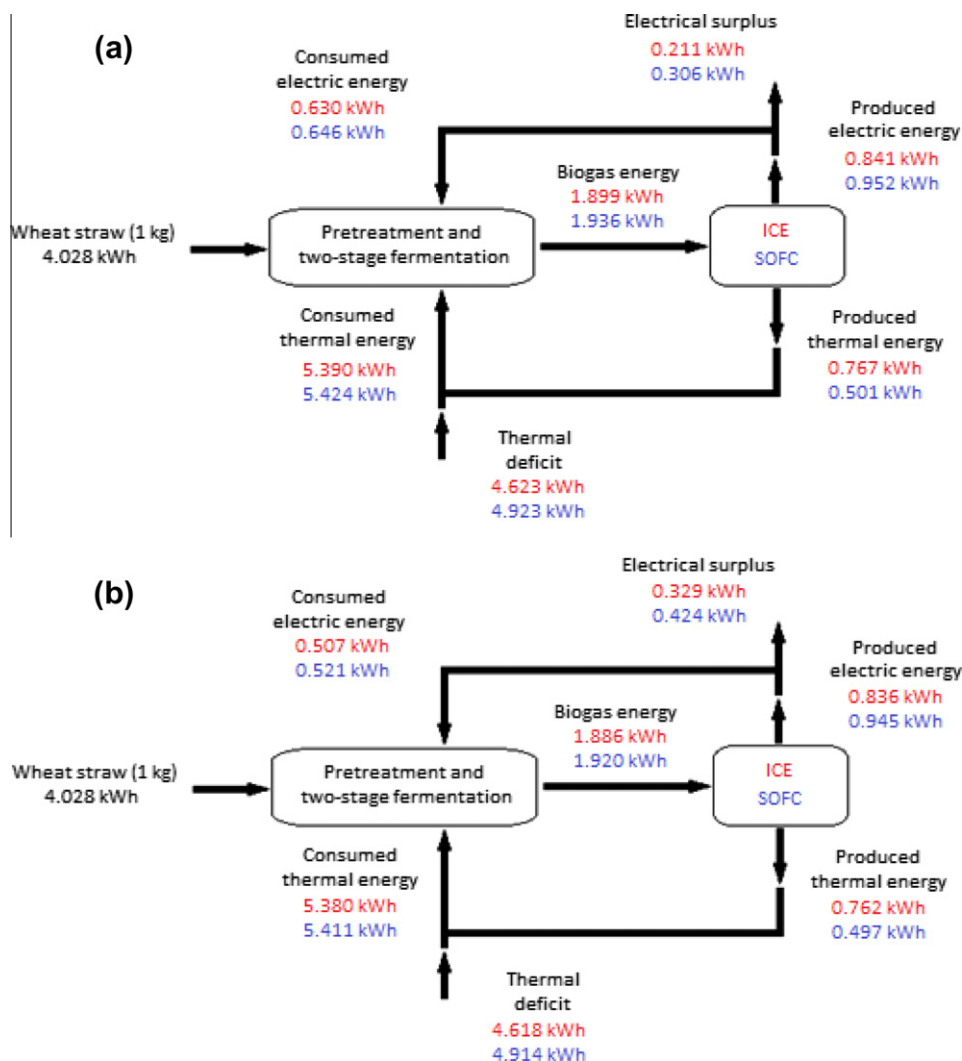


Fig. 4. Energy quantities referred to 1 kg of wheat straw (primary fuel): (a) net, (b) in case of thermal recovery from other processes.

Table 6
Digesters for the final fermentation.

| | Bio-hydrogen reactor [m ³] | Biogas reactor [m ³] |
|---------------------------|--|----------------------------------|
| 250 kW _{EL} SOFC | 21.3 | 2554.7 |
| 2700 kW _{EL} ICE | 256.2 | 30748.8 |

ethanol, steam explosion and enzymatic hydrolysis, the results are reported in Table 5. The optimization 2 is significantly different than optimization 1: the optimum point in terms of maximum net electric energy produced does not coincide with the optimum point in terms of maximum biogas production by the plant.

In the optimization 2 operation point, compared to optimization 1, the systems produces 16–17% less biogas and 18–20% higher net electric energy.

Also, the optimum point is strictly related to the final utilization technology considered. Therefore, the optimization of the overall integrated systems is really an integrated process, which strictly links the optimum biogas production point to the choice of the final biogas utilization technology.

4. Discussion

4.1. Analysis and comparison of the complete energy pathway

In order to compare the two complete energy pathways, the optimization 2 conditions have been selected, which obtained the better results. Fig. 4 shows the energy balance in the best production process (pre-impregnation with ethanol, steam explosion, enzymatic hydrolysis). Among the ICEs, the Type 620, with the highest electric efficiency has been considered. As described above, all the energy quantities refer to the unit of starting biomass (the primary fuel), that is 1 kg of wheat straw, with a LHV = 14.5 MJ/kg.

As noticed above, the integration of a SOFC allows a higher net electric energy to be obtained: in particular, the biogas production process operates with a higher energy consumption, but the final net effect is better compared to the ICE; at the same time, the lower thermal efficiency of the SOFC determines a lower thermal recovery, and thus the thermal integration is higher compared to ICE.

Considering to supply the thermal deficit with a standard heat generator ($\eta = 0.9$), the global efficiency (from primary sources)

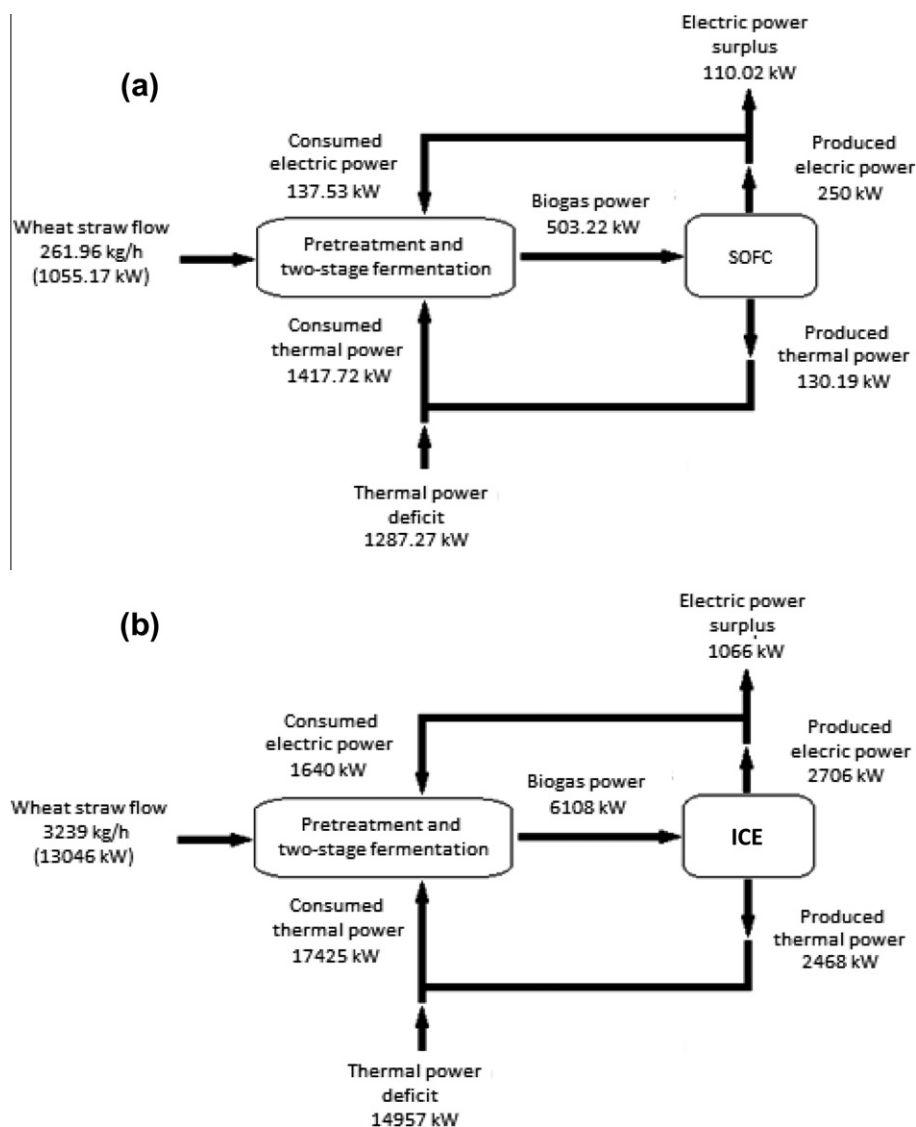


Fig. 5. Power values: (a) 250 kW_{EL} SOFC and (b) 2700 kW_{EL} ICE.

of the complete energy path results in 2.1% (ICE) and 3.0% (SOFC). Both the values are quite low.

Considering the thermal energy, the step with the highest consumption is the steam explosion (54% of total consumption) with also the highest temperatures (around 200–220 °C). But, in general, all the thermal consumptions are difficult to reduce in the present configuration of the process.

Anyway, the thermal consumptions could be supplied using thermal flows from renewable sources (e.g. concentration solar power, due to the high temperatures), or from thermal wastes from other agricultural or industrial processes.

Therefore, considering an optimization procedure based on the assumption of possible recovery of waste heat, the energy efficiency of the complete system could show a significant improvement. In particular, it has to be remembered that the operation point is evaluated through an optimization procedure: in this case, the operation points derives from the availability of recovered or renewable heat, but also from the reduction of boiler's electrical consumption, and in general from the shift of the optimal design point towards a area of lower energy-consumption (due to the increase of the renewable electric input also for heat management). In that case, the global efficiency could increase significantly, as shown in Fig. 4.

In the conditions of heat recovery from an external process, the highest electric consumptions are due to the enzymatic hydrolysis (30%) and to the fermentation (55%).

In the enzymatic hydrolysis the consumptions come from the recirculation pump and the bed mixing, but also from the compressor feeding the pneumatic valves. In the fermentation step the consumptions come from the recirculation pumps which operate in continuous cycle. These consumptions are necessary, but could be reduced using other devices (e.g. a bubbler for bed movement, in place of recirculation pumps).

In those conditions, the global efficiency (from primary sources) of the complete pathway will become equal to 8.2% (ICE) and 10.5% (SOFC), while the gross electric efficiency will become equal to 20.8% (ICE) and (23.5%). There are, therefore, margins for the improvement of the energy balance of the considered energy pathways.

4.2. Scale-up of the plants

In order to consider realistic sizes of such plants based on the integration of a biogas production path and a final biogas user, a scale-up of the plants has been considered: a 250 kWe SOFC plant, and a 2.7 MWe ICE plant. The sizes have been based on the available technologies, and on a range which is realistic for a use in an agricultural context. In those conditions, the size of the digesters for the final fermentation is shown in Table 6.

The power exchanged in the plants is shown in Fig. 5:

As expected, the thermal deficit is significant. Therefore, for the energy balance of such kind of integrated systems, it is fundamental to have the possibility of recovery of some heat wastes from other processes, or to drastically modify the steps of the process which are more demanding in terms of thermal energy.

The comparison between ICE and SOFC shows the better performance of the integrated plants based on SOFC: therefore, it is shown that the electric efficiency of the final user of the biogas

has a significant role in improving the energy balance of the complete energy pathway starting from agricultural residues.

5. Conclusions

The energy analysis of the complete biomass-to-biogas process (impregnation; steam explosion; enzymatic hydrolysis; two-step anaerobic fermentation) has been performed, with an optimization of the complete thermo-chemical and biological process. The analysis has been based on a pilot plant of the complete process.

The biogas-to-electricity step has been analyzed, considering two alternative of CHP plants: ICE and SOFC. The results demonstrate that the integration of the biomass-to-biogas process with the biogas-to-electricity plant allows a final positive (10%) electricity balance, while a deficit in thermal energy still exist. Finally, the comparison shows the better performance of the integrated plants based on SOFC.

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